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APPLICATION NO.	FILING DATE	FIRST NAMED INVENTOR	ATTORNEY DOCKET NO.	CONFIRMATION NO.
10/578,508	09/26/2006	Daniel Kopf	117891	9426

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P.O. BOX 320850
ALEXANDRIA, VA 22320-4850

EXAMINER	
ZHANG, YUANDA	

ART UNIT	PAPER NUMBER
2828	

MAIL DATE	DELIVERY MODE
07/17/2008	PAPER

Please find below and/or attached an Office communication concerning this application or proceeding.

The time period for reply, if any, is set in the attached communication.

Office Action Summary	Application No.	Applicant(s)
	10/578,508	KOPF ET AL.
	Examiner	Art Unit
	YUANDA ZHANG	2828

-- *The MAILING DATE of this communication appears on the cover sheet with the correspondence address* --

Period for Reply

A SHORTENED STATUTORY PERIOD FOR REPLY IS SET TO EXPIRE 3 MONTH(S) OR THIRTY (30) DAYS, WHICHEVER IS LONGER, FROM THE MAILING DATE OF THIS COMMUNICATION.

- Extensions of time may be available under the provisions of 37 CFR 1.136(a). In no event, however, may a reply be timely filed after SIX (6) MONTHS from the mailing date of this communication.
- If NO period for reply is specified above, the maximum statutory period will apply and will expire SIX (6) MONTHS from the mailing date of this communication.
- Failure to reply within the set or extended period for reply will, by statute, cause the application to become ABANDONED (35 U.S.C. § 133). Any reply received by the Office later than three months after the mailing date of this communication, even if timely filed, may reduce any earned patent term adjustment. See 37 CFR 1.704(b).

Status

1)☒ Responsive to communication(s) filed on *26 September 2006*.

2a)☐ This action is **FINAL**. 2b)☒ This action is non-final.

3)☐ Since this application is in condition for allowance except for formal matters, prosecution as to the merits is closed in accordance with the practice under *Ex parte Quayle*, 1935 C.D. 11, 453 O.G. 213.

Disposition of Claims

4)☒ Claim(s) *1-17* is/are pending in the application.

4a) Of the above claim(s) _____ is/are withdrawn from consideration.

5)☐ Claim(s) _____ is/are allowed.

6)☒ Claim(s) *1-17* is/are rejected.

7)☐ Claim(s) _____ is/are objected to.

8)☐ Claim(s) _____ are subject to restriction and/or election requirement.

Application Papers

9)☐ The specification is objected to by the Examiner.

10)☒ The drawing(s) filed on *26 September 2006* is/are: a)☒ accepted or b)☐ objected to by the Examiner.

Applicant may not request that any objection to the drawing(s) be held in abeyance. See 37 CFR 1.85(a).

Replacement drawing sheet(s) including the correction is required if the drawing(s) is objected to. See 37 CFR 1.121(d).

11)☐ The oath or declaration is objected to by the Examiner. Note the attached Office Action or form PTO-152.

Priority under 35 U.S.C. § 119

12)☐ Acknowledgment is made of a claim for foreign priority under 35 U.S.C. § 119(a)-(d) or (f).

a)☐ All b)☐ Some * c)☐ None of:

1.☐ Certified copies of the priority documents have been received.

2.☐ Certified copies of the priority documents have been received in Application No. _____.

3.☐ Copies of the certified copies of the priority documents have been received in this National Stage application from the International Bureau (PCT Rule 17.2(a)).

* See the attached detailed Office action for a list of the certified copies not received.

Attachment(s)

1) ☒ Notice of References Cited (PTO-892)

2) ☐ Notice of Draftsperson's Patent Drawing Review (PTO-948)

3) ☒ Information Disclosure Statement(s) (PTO/SB/08) Paper No(s)/Mail Date *07/21/06*.

4) ☐ Interview Summary (PTO-413) Paper No(s)/Mail Date. _____ .

5) ☐ Notice of Informal Patent Application

6) ☐ Other: _____.

DETAILED ACTION

Claim Objections

1. Claim 3 is objected to because of the following informalities: word "reflection" should be changed to "reflections". Appropriate correction is required.

Claim Rejections - 35 USC § 112

2. The following is a quotation of the first paragraph of 35 U.S.C. 112:

> The specification shall contain a written description of the invention, and of the manner and process of making and using it, in such full, clear, concise, and exact terms as to enable any person skilled in the art to which it pertains, or with which it is most nearly connected, to make and use the same and shall set forth the best mode contemplated by the inventor of carrying out his invention.

3. Claim 1 is rejected under 35 U.S.C. 112, first paragraph, as failing to comply with the written description requirement. The claim(s) contains subject matter which was not described in the specification in such a way as to reasonably convey to one skilled in the relevant art that the inventor(s), at the time the application was filed, had possession of the claimed invention. In re claim 1, the limitation of "the pulse stretcher having a minimum of 3rd order dispersion with a maximum of 2nd order dispersion" is not reasonably conveyed in view of the specification. The specification suggests that a SF57 glass or a SF10 glass, given as an example, is used as a pulse stretcher. In paragraph [0023], the specification then discloses that "An advantageous ratio of the 2.sup.nd order (positive) dispersion to the 3.sup.rd order (positive) dispersion should be achieved, i.e. a minimum 3.sup.rd order dispersion in combination with maximum 2.sup.nd order dispersion." The claim language suggests that a pulse stretcher as "a specially designed component". However, not given enough disclosure in the specification, one cannot determine what special design is implemented in order to

achieve a minimum of 3rd order dispersion with a maximum of 2nd order dispersion. Therefore, the Examiner has reasonably concluded based on the lack of disclosure in the specification that a SF57 glass or a SF10 glass has an inherent property of a minimum of 3rd order dispersion with a maximum of 2nd order dispersion.

4. The following is a quotation of the second paragraph of 35 U.S.C. 112:

> The specification shall conclude with one or more claims particularly pointing out and distinctly claiming the subject matter which the applicant regards as his invention.

5. Claim 17 recites the limitations "the relationship" in line 1 and "the Treacy design". There is insufficient antecedent basis for this limitation in the claim. The Examiner believes that "the relationship" should be replaced with "a relationship" and "the Treacy design" should be replaced with "Treacy design".

Claim Rejections - 35 USC § 103

6. The following is a quotation of 35 U.S.C. 103(a) which forms the basis for all obviousness rejections set forth in this Office action:

> (a) A patent may not be obtained though the invention is not identically disclosed or described as set forth in section 102 of this title, if the differences between the subject matter sought to be patented and the prior art are such that the subject matter as a whole would have been obvious at the time the invention was made to a person having ordinary skill in the art to which said subject matter pertains. Patentability shall not be negatived by the manner in which the invention was made.

7. Claims 1-4, 6-9, 11-12, 14 and 16-17 are rejected under 35 U.S.C. 103(a) as being unpatentable over T.B. Norris ("Femtosecond pulse amplification at 250 kHz with a Ti:sapphire regenerative amplifier and application to continuum generatino" Optical Society of America 2412 Optics Letters 17(1992) July 15, No. 14) in view of M.

Hentschel et al (Generation of 0.1-TW optical pulses with a single-stage Ti:sapphire amplifier at a 1-kHz repetition rate" Appl. Phys. B 70 [Suppl.], S161-S164 2000).

8. In re claim 1, T.B. Norris discloses laser system having a repetition rate greater than 50 KHz (a repetition rate of 76 MHz) according to the principle of the regenerative amplifier (Ti: sapphire regenerative amplifier), comprising at least an amplifying laser medium (Ti: sapphire laser medium), a laser resonator (Ti: sapphire oscillator regenerative amplifier shown in figure 2) having at least one resonator mirror (mirror next to the Q-switch) and at least one modulator (Q-switch), and a pump source (cw argon pump source) for pumping the laser medium (see figure 1).

9. T.B. Norris does not disclose wherein the laser resonator has a pulse stretcher as a specially designed component having a structure- and/or material-related dispersive effect, the pulse stretcher having minimum 3rd order dispersion with maximum 2nd order dispersion.

10. However, with reference to figure 3, M. Hentschel et al disclose a pulse stretcher which includes a SF57 glass (page S162, first paragraph under 2 Setup) having a minimum 3rd order dispersion with a maximum 2nd order dispersion (According to the 112 rejection above, the pulse stretcher as SF57 has an inherent material property of having a minimum 3rd order dispersion with a maximum 2nd order dispersion).

11. It would have been obvious to one having ordinary skill in the art at the time the invention was made to have modified the laser system of T.B. Norris with a pulse stretcher having a material property of a minimum of 3rd order dispersion with a maximum of 2nd order dispersion as taught by M. Hentschel et al in order to obtain high

efficiency pulse stretching without introducing any alignment issue (page S162, first paragraph under 2 Setup).

12. In re claim 2, M. Hentschel et al disclose wherein the pulse stretcher has a block of highly dispersive material (inherent property of SF57).

13. In re claim 3, M. Hentschel et al disclose multiple reflections takes place within the block (inherent for SF57).

14. In re claims 4 and 16, M. Hentschel et al disclose a dispersive layer which is a used as a folding mirror (pulse stretcher includes a plurality of folding mirror, see figure 3).

15. In re claim 6, T.B. Norris / M. Hentschel et al have disclosed the claimed invention above except wherein the laser medium has an inversion life (storage time) greater than 1 ms. It would have been obvious to one having ordinary skill in the art at the time the invention was made to choose a laser medium having an inversion life of greater than 1 ms in order to obtain a higher output power, since it has been held to be within the general skill of a worker in the art to select a known material on the basis of its suitability for the intended use as a matter of obvious design choice. *In re Leshin,* 125 USPQ 416.

16. In re claim 7, T.B. Norris discloses wherein a femtosecond oscillator for inputting seed pulses, the femtosecond oscillator being formed and arranged in such a way that the seed pulses are femtosecond pulses or picosecond pulses on input into the laser resonator (second paragraph, page 1009).

17. In re claim 8, T.B. Norris discloses wherein an electro-optical switching element as modulator (Q-switch) (see figure 2).

18. In re claim 9, T.B. Norris discloses wherein a pulse compressor (compressor consists of a plurality of SF10 prism) is outside the laser resonator (see figure 1).

19. In re claim 11, M. Hentschel et al disclose wherein the pump source is a laser diode (diode pumped Nd: YVO4, see figure 3).

20. In re claim 12, M. Hentschel et al disclose wherein the highly dispersive material is SF57 glass block (page S162, first paragraph under 2 Setup).

21. In re claim 14, T.B. Norris / M. Hentschel et al have disclosed the claimed invention above except wherein the laser medium is a Yb:glass or Yb:crystal. It would have been obvious to one having ordinary skill in the art at the time the invention was made to choose a laser medium of Yb:glass or Yb:crystal in order to obtain a longer inversion time which increase output power (see applicant admitted prior art "Directly diode-pumped Yb:KY(WO4)2 regenerative amplifier"), since it has been held to be within the general skill of a worker in the art to select a known material on the basis of its suitability for the intended use as a matter of obvious design choice. *In re Leshin,* 125 USPQ 416.

22. In re claim 17, T.B. Norris disclose a relationship of the pulse compressor outside the laser resonator is according to Treacy design (inherent, based on the claim language, the Examiner notes that Treacy design is satisfied if the pulse compressor is placed outside of the laser resonator).

23. Claims 5 and 13 are rejected under 35 U.S.C. 103(a) as being unpatentable over T.B. Norris ("Femtosecond pulse amplification at 250 kHz with a Ti:sapphire regenerative amplifier and application to continuum generatino" Optical Society of America 2412 Optics Letters 17(1992) July 15, No. 14) in view of M. Hentschel et al ("Generation of 0.1-TW optical pulses with a single-stage Ti:sapphire amplifier at a 1-kHz repetition rate" Appl. Phys. B 70 [Suppl.], S161-S164 2000) as applied to claim 1 above, and further in view of Pang (US PG Pub 2003/0095320 A1).

24. In re claim 5, T.B. Norris / M. Hentschel et al have disclosed the claimed invention above except wherein the pulse stretcher has at least two reflecting surfaces, the surfaces being arranged in such a way that the surfaces are oriented - relative to one another and - at an opening angle, and the laser beam is reflected at least twice at at least one of the surfaces. However, with reference to figure 2, Pang discloses a pulse stretcher (50) has at least two reflecting surfaces (70 & 72), the surfaces being arranged in such a way that the surfaces are oriented - relative to one another (facing each other) and - at an opening angle (angle ɵ), and the laser beam is reflected at least twice at at least one of the surfaces (paragraph [0028]). It would have been obvious to one having ordinary skill in the art at the time the invention was made to have modified the laser system of T.B. Norris / M. Hentschel et al with an alternative pulse stretcher as taught by Pang in order to obtain a tunable pulse stretcher.

25. In re claim 13, Pang discloses wherein the opening angle is adjustable (grating 70 is tunable by adjusting its angle, see figure 2).

26. Claims 10 and 15 are rejected under 35 U.S.C. 103(a) as being unpatentable over T.B. Norris ("Femtosecond pulse amplification at 250 kHz with a Ti:sapphire regenerative amplifier and application to continuum generation" Optical Society of America 2412 Optics Letters 17(1992) July 15, No. 14) in view of M. Hentschel et al (Generation of 0.1-TW optical pulses with a single-stage Ti:sapphire amplifier at a 1-kHz repetition rate" Appl. Phys. B 70 [Suppl.], S161-S164 2000) as applied to claim 1 above, and further in view of H. Takada et al ("Large-ratio stretch and recompression of sub-10-fs pulses utilizing dispersion managed devices and a spatial light modulator", Appl. Phys. B 74 [Suppl.], S253-S257 2002).

27. In re claims 10 and 15, T.B. Norris / M. Hentschel et al have disclosed the claimed invention above except wherein the pulse compressor has s dispersive grating having less than 1200 lines/mm. However, with reference to figure 6, H. Takada et al disclose a dispersion compressor includes a pair of dispersive grating with 200 lines/mm for compressing pulses. It would have been obvious to one having ordinary skill in the art at the time the invention was made to have a pulse compressor with a pair of dispersive grating of less than 1200 lines/mm to compress pulses since it is a known alternative to a pulse compressor comprising a plurality of prism.

Conclusion

Any inquiry concerning this communication or earlier communications from the examiner should be directed to YUANDA ZHANG whose telephone number is

(571)270-1439. The examiner can normally be reached on Monday-Thursday, 7:30am-6:00p EST.

If attempts to reach the examiner by telephone are unsuccessful, the examiner's supervisor, Minsun Harvey can be reached on 571-272-1835. The fax phone number for the organization where this application or proceeding is assigned is 571-273-8300.

Information regarding the status of an application may be obtained from the Patent Application Information Retrieval (PAIR) system. Status information for published applications may be obtained from either Private PAIR or Public PAIR. Status information for unpublished applications is available through Private PAIR only. For more information about the PAIR system, see http://pair-direct.uspto.gov. Should you have questions on access to the Private PAIR system, contact the Electronic Business Center (EBC) at 866-217-9197 (toll-free). If you would like assistance from a USPTO Customer Service Representative or access to the automated information system, call 800-786-9199 (IN USA OR CANADA) or 571-272-1000.

/YZ/
07/11/08

/Minsun Harvey/
Supervisory Patent Examiner, Art Unit 2828

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Sheet 1 of 1

Form PTO-1449 (REV. 1/06) US Dept. of Commerce PATENT & TRADEMARK OFFICE INFORMATION DISCLOSURE STATEMENT (Use several sheets if necessary)	ATTY DOCKET NO. 117891	APPLICATION NO. 10/578,508
	APPLICANT(S) Daniel KOPF et al.	
	FILING DATE May 8, 2006	GROUP 2828

U.S. PATENT DOCUMENTS

Examiner Initials	Cite No.	Document Number	Date	Name
/YZ/	1	US 2003/0095320	05/22/2003	Pang

FOREIGN PATENT DOCUMENTS

Examiner Initials	Cite No.	Document Number	Date	Country	With English Abstract	With English Translation
	2	DE 100 63 976 A1	07/04/2002	Germany		
	3	WO 2004/107513 A2	12/09/2004	PCT	x	

OTHER DOCUMENTS

Examiner Initials	Cite No.	(Including Author, Title, Date, Pertinent Pages, etc.)
	4	Kopf et al., US Provisional Patent Application No. 60/474,250, filed May 30, 2003
	5	Kopf et al., U.S. Provisional Patent Application No. 60/442,917, filed January 28, 2003
	6	Maurice Pessot et al., "Chirped Pulse Amplification of 300 fs Pulses in an Alexandrite Regenerative Amplifier," IEEE, Journal of Quantum Electronics, Vol. 25, No. 1, January 1989, pp. 61-66.
	7	T. B. Norris, "Femtosecond pulse amplification at 250 kHz with a Ti:sapphire regenerative amplifier and application to continuum generation," Optics Letter, July 15, 1992, No. 14, New York, NY, pp. 1009-1011.
	8	Taiha Joo et al., "Ti:sapphire regenerative amplifier for ultrashort high-power multikilohertz pulses without an external stretcher," Feb. 15, 1995, Vol. 20, No. 4, Optics Letter, pp. 389-391.
	9	Hsiao-hua Liu et al., "Directly diode-pumped Yb:KY$(WO_4)_2$ regenerative amplifiers," Optics Letters, Vol. 27, No. 9, May 1, 2002
	10	Guanghua Cheng et al., "A compact Ti:sapphire femtosecond pulse amplifier without stretcher at high repetition rate," Chinese Optics Letter, April 20, 2003, Vol. 1, No. 4., pp. 225-227.
	11	Agarwal, "Nonlinear Fiber Optics," Academic Press 1989, pg. 150.

EXAMINER /Yuanda Zhang/	DATE CONSIDERED 06/26/2008
Examiner: Initial if citation considered, whether or not citation is in conformance with M.P.E.P. 609; draw line through citation if not in conformance and not considered. Include copy of this form with next communication to applicant.	

Date: July 21, 2006

Notice of References Cited	Application/Control No. 10/578,508	Applicant(s)/Patent Under Reexamination KOPF ET AL.	
	Examiner YUANDA ZHANG	Art Unit 2828	Page 1 of 1

U.S. PATENT DOCUMENTS

*		Document Number Country Code-Number-Kind Code	Date MM-YYYY	Name	Classification
	A	US-			
	B	US-			
	C	US-			
	D	US-			
	E	US-			
	F	US-			
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	M	US-			

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	N					
	O					
	P					
	Q					
	R					
	S					
	T					

NON-PATENT DOCUMENTS

*		Include as applicable: Author, Title Date, Publisher, Edition or Volume, Pertinent Pages)
	U	M. Hentschel et al "Generation of 0.1-TW optical pulses with a single-stage Ti:sapphire amplifier at a 1-kHz repetition rate" Appl. Phys. B 70 [Suppl.], S161-S164 2000
	V	H. Takada et al "Large-ratio stretch and recompression of sub-10-fs pulses utilizing dispersion managed devices and a spatial light modulator", Appl. Phys. B 74 [Suppl.], S253-S257 2002.
	W	
	X	

*A copy of this reference is not being furnished with this Office action. (See MPEP § 707.05(a).)
Dates in MM-YYYY format are publication dates. Classifications may be US or foreign.

Appl. Phys. B 74 [Suppl.], S253–S257 (2002)
DOI: 10.1007/s00340-002-0883-y

Applied Physics B
Lasers and Optics

H. TAKADA✉
M. KAKEHATA
K. TORIZUKA

Large-ratio stretch and recompression of sub-10-fs pulses utilizing dispersion managed devices and a spatial light modulator

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Revised version: 21 November 2001
Published online: 27 June 2002

ABSTRACT We demonstrate stretch and recompression of a sub-10-fs pulse utilizing a broadband pulse stretcher, a dispersion compensator with a spatial light modulator, and a broadband pulse compressor for ~ 10-fs Ti:sapphire chirped-pulse amplification system. Our calculation suggests that the dispersion compensator is useful for dispersion compensation of a Ti:sapphire chirped-pulse amplification system, including multi-pass amplifiers.

PACS 42.60.By ; 42.65.Re

1 Introduction

In the last few years, the pulse duration of the Ti:sapphire chirped-pulse amplification (CPA) [1] system has been reduced. Barty et al. [2] demonstrated the generation of 18-fs 4.4-TW pulses at a 10 Hz repetition rate utilizing a cylindrical mirror-based pulse stretcher and a regenerative amplifier with an etalon for compensation of gain narrowing. Yamakawa et al. [3] demonstrated the generation of 20-fs, 100-TW pulses at a 10-Hz repetition rate using the above techniques. Zeek et al. [4] demonstrated the generation of 15-fs, 1-mJ pulses at a 1-kHz repetition rate using a deformable mirror for the reduction of residual dispersions of the output pulses. Verluise et al. [5] demonstrated the generation of 17-fs pulses using an acousto-optic programmable dispersive filter (AOPDF) for the reduction of residual dispersions of the output pulses. Hentschel et al. [6] demonstrated the generation of 18-fs 0.1-TW pulses at a 1-kHz repetition rate using a SF57 glass block for the stretching of a seed pulse and an eight-pass amplifier with a dielectric multilayer filter for compensation of gain narrowing. Bagnoud et al. [7] demonstrated the generation of 20-fs 1-TW pulses at a 1-kHz repetition rate using a pulse stretcher with an Öffner-type telescope and a regenerative amplifier with a birefringent filter for compensation of gain narrowing.

To reduce the pulse width to ~ 10 fs, we need a broadband (> 250 nm) pulse stretcher, in which residual aberrations are negligibly small, and a broadband pulse compressor, which compresses a chirped pulse to a ~ 10-fs pulse with negligibly small satellite pulses and a pedestal. In this paper, we demonstrate stretch and recompression of a sub-10-fs pulse using a broadband pulse stretcher, a dispersion compensator with a spatial light modulator, and a broadband pulse compressor for a ~ 10-fs Ti:sapphire chirped-pulse amplification system. To confirm the validity of a dispersion compensator to a CPA system, we calculated the output pulse of a CPA system, including a pulse stretcher, a dispersion compensator, two multi-pass Ti:sapphire amplifiers, and a pulse compressor. Our calculation suggests that a dispersion compensator is useful for dispersion compensation of a Ti:sapphire CPA system including multi-pass amplifiers.

2 Stretch and recompression using a pulse stretcher and a pulse compressor

Generally, a pulse stretcher for a chirped-pulse amplification system, which generates < 100-fs pulses, consists of gratings and a telescope. If the spectral width of the pulse is relatively wide (> 200 nm) and the pulse width of the chirped pulse is relatively long (> 100 ps), it is not easy to decrease the aberration of the telescope to a negligibly small value. We adopt a pulse stretcher with a telescope, which consists of a concave and a convex mirror [8, 9]. Figure 1 shows

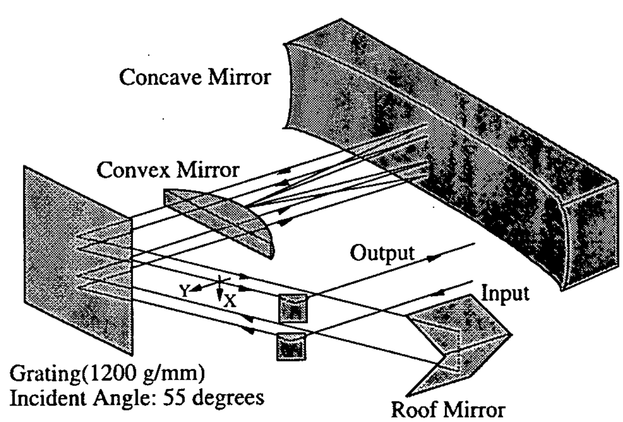

FIGURE 1 Schematic of a pulse stretcher

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a schematic of the pulse stretcher. Since the aberration of this telescope is relatively small, the high-order dispersions of this stretcher are nearly the reverse of those of the compressor. Therefore, this stretcher is suitable for the CPA system, including a multi-pass amplifier chain having relatively small material dispersions. For ~ 10-fs multi-TW pulse generation, the results of our calculations suggest the residual dispersions of the CPA system, which consists of this type of stretcher, multi-pass amplifiers, a pair of prisms, and a pulse compressor, can be reduced to a negligibly small value [10]. The pulse stretcher stretches the ~ 10-fs pulse to ~ 300 ps to decrease the B-integral value to $\ll \pi$ in the amplifier chain. By considering the spectral width of the pulse and the amount of dispersion, which satisfies the condition of stretch, we decide upon the parameters of the pulse stretcher.

In the case of an Öffner-type telescope, centers of curvatures of a concave mirror and a convex mirror coincide at a single point [11], but those of the concave mirror and the convex mirror, which are components of our pulse stretcher, do not coincide at a single point. Based on our calculation utilizing ray tracing [10], if an Öffner-type telescope is utilized in a pulse stretcher γ with wide spectral range (> 200 nm), it is difficult to decrease an aberration of an Öffner-type γ telescope to a negligibly small value. The results of our calculation suggest that the optimization of a radius curvature and the position of a convex mirror is useful for decreasing an aberration of a telescope for a pulse stretcher. Figure 2 shows the wavelength dependence of the direction angles of the output beam from the pulse stretchers. The radius curvature of the concave mirror is 1 m. The distance between the concave mirror and the convex mirror is 0.5 m, and the distance between the concave mirror and the grating is 0.8 m. In this figure, R, X and Y show the radius curvature of the convex mirror, the vertical direction and the horizontal direction, respectively. The diameter of the output beam is 2 mm. This shows that the use of an Öffner-type telescope causes the horizontal spectral distribution, because the direction angles of the output beam are not negligibly small compared with the divergence of the output beam. If the radius curvature of a convex mirror is optimized, the horizontal spectral distribution can be reduced remarkably. If the distance between a grating and a concave mirror is a radius curvature of a concave mirror, an optimized radius curvature of a convex mirror is half a radius curvature of a concave mirror. As a distance between a grating and a concave mirror becomes shorter, an optimized radius curvature of a convex mirror becomes longer.

We constructed the pulse stretcher based on the results of our calculation. The curvatures of the concave mirror and the convex mirror, which we actually use, are 998 mm and 519 mm, respectively. The distance between the concave mirror and the convex mirror is 499 mm. This distance must be adjusted precisely, because the error of the distance causes the horizontal spectral distribution. The method of adjusting the distance precisely is to adjust the distance to decrease the horizontal spectral distribution so that it is as small as possible. The size of the concave mirror is 500 mm(W) × 100 mm(H) × 80 mm(D). The size of the convex mirror is 300 mm(W) × 10 mm(H) × 50 mm(D). The thinness of the convex mirror is very important to reduce the residual vertical and horizontal spectral distributions of the output beam. As the vertical positions of the beams over the convex mirror and those under the convex mirror become closer, the residual vertical and horizontal spectral distributions of the output beam become smaller. The number of grooves of the grating for the pulse stretcher is 1200 g/mm. The ruled size of the grating is 206 mm(W) × 102 mm(H). The incidence angle of the grating is 55°. The distance between the concave mirror and the grating is 800 mm. The bandwidth of the pulse stretcher is ~ 340 nm. The optic which limits the bandwidth is the concave mirror. The pulse compressor consists of a pair of two parallel gratings, and the optical path length between these is ~ 36 cm. The ruled size of the first grating is 102 mm(W) × 102 mm(H). The ruled size of the second grating is 206 mm(W) × 102 mm(H). The incidence angle of the first grating is ~ 55°.

At first, we tried to stretch and recompress sub-10-fs pulses using only a pulse stretcher and a pulse compressor. The ~ 8-fs pulse train from a mode-locked Ti:sapphire laser with commercial chirped mirrors (Layer Tec) and a pair of fused silica prisms is sent to the pulse stretcher to be stretched to ~ 300 ps. The pulse compressor recompresses ~ 300-ps chirped pulses to ~ 10 fs. Figure 3 shows the meas-

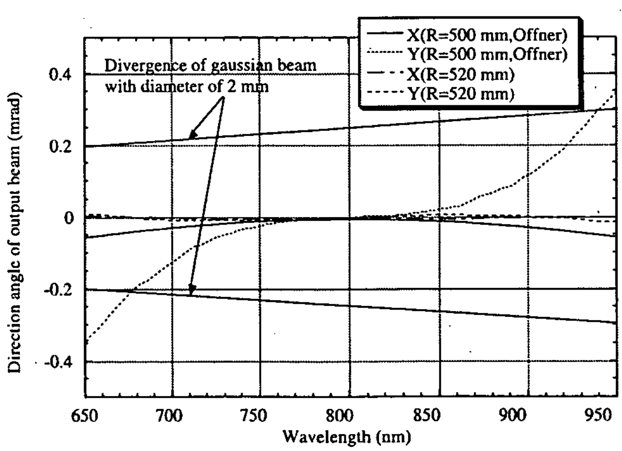

FIGURE 2 Wavelength dependence of the direction angles of the output beam from the pulse stretchers

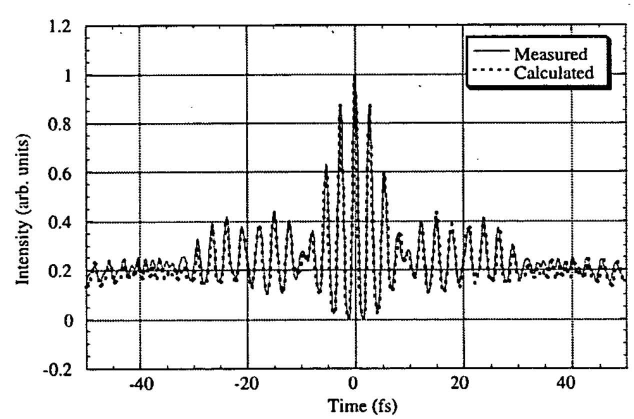

FIGURE 3 Measured fringe-resolved autocorrelation trace (*solid line*) and calculated autocorrelation trace (*dotted line*) of the recompressed pulses

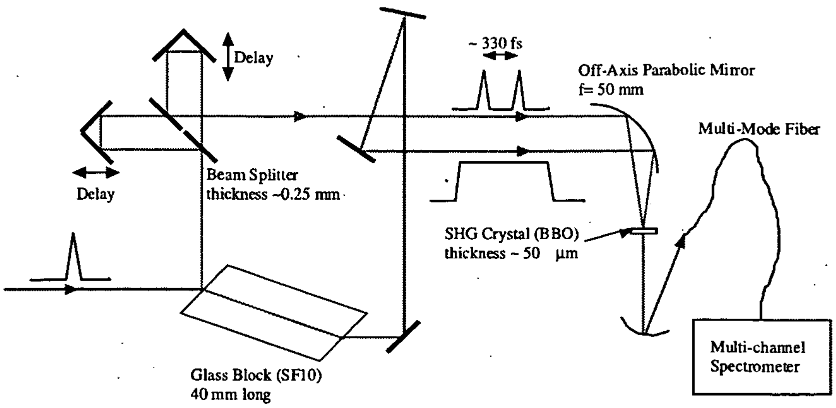

FIGURE 4 Schematic of spectral phase interferometry for direct electric-field reconstruction (SPIDER)

ured fringe-resolved autocorrelation trace (solid line) of the recompressed pulse. The measured pulse width of the recompressed pulse is ~ 10 fs, but the large pedestal seems to exist. Therefore, we measured the phase of the recompressed pulse using spectral phase interferometry for direct electric-field reconstruction (SPIDER) [12]. Figure 4 shows a schematic of SPIDER. The *S*-polarized pulse is divided into two pulses on the surface of a SF10 glass block 40 mm long. One pulse broadened by the glass block; the other is divided into two pulses by a commercial beam splitter (CVI FABS-800-45SET-25.4-0.25-UV). The thickness of the beam splitters is 0.25 mm. These two pulse replicas are delayed with respect to one another by ~ 330 fs. These pulses and a chirped pulse are focused by an off-axis parabolic mirror with a focusing length of 50 mm. These pulses are frequency mixed with a chirped pulse in a BBO crystal with a thickness of ~ 50 μm. Each pulse replica is frequency mixed with a different time slice, and hence spectral slice, of a stretched pulse, and consequently the upconverted pulses are spectrally sheared. The resulting interferogram is resolved with a multi-channel spectrometer with a Peltier-cooled CCD detector. The number of the channels of the spectrometer is 1024. The minimum input power of this SPIDER system is less than 6 mW.

Figure 5 shows the phase (dotted line) and the spectra (solid line) of the recompressed pulse. Figure 3 shows the autocorrelation trace (dotted line) calculated from the measured spectra and the measured phase. The measured autocorrelation trace and the calculated autocorrelation trace agree well with each other. This figure shows that the satellite pulse and the pedestal are not negligibly small, and are due to the residual dispersion of the pulse stretcher and the pulse compressor.

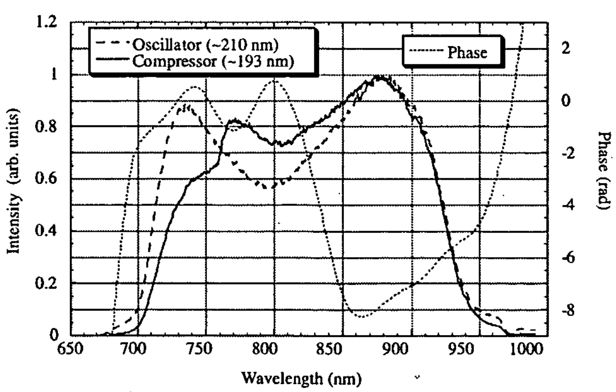

FIGURE 5 Spectra (*dashed line*) of the pulse from the oscillator, spectra (*solid line*) and phase (*dotted line*) of the recompressed pulse

3 Using a dispersion compensator with a spatial light modulator

To cancel the residual dispersion of the pulse stretcher and the pulse compressor, we need the optics, which cancel an arbitrary dispersion, because the shape of the residual dispersion of the pulse stretcher and the pulse compressor is complex. For this purpose, a deformable mirror [4], an acousto-optic programmable dispersive filter (AOPDF) [5], a spatial light modulator [13, 14], etc. are used. We use a dispersion compensator with a spatial light modulator for reduction of the residual dispersion, because this compensator can generate the spectral phase with a relatively complex shape. Xu et al. [15] used such a dispersion compensator for generation of 6-fs pulses. Figure 6 shows a schematic of the dispersion compensator. The dispersion compensator consists of two gratings, two concave mirrors, and the commercial spatial light modulator (CRI SLM-256-NIR). The number of grooves of the gratings is 200 g/mm. The radius curvature of the concave mirrors is 0.4 m. A width of a pixel of the spatial light modulator is 100 μm. The beam size on the spatial light modulator is 100 μm. This size is as large as the width of the pixel, therefore the resolution power of a spatial light modulator can be used. The spectral width per a channel is

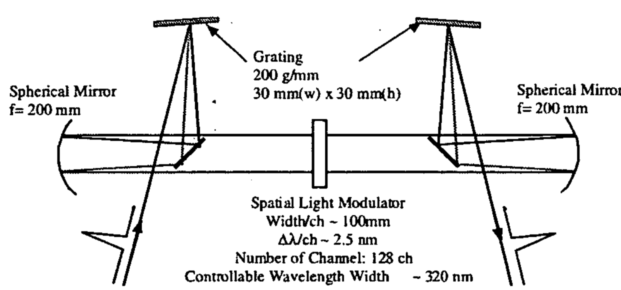

FIGURE 6 Schematic of the dispersion compensator

~ 2.5 nm, the number of pixels of the spatial light modulator is 128, and the bandwidth of the compensator is ~ 320 nm. To cancel the residual dispersion precisely, we measured the wavelength dependence of the retardation of the liquid crystal used in the spatial light modulator. We calculated the wavelength dependence of the channels of the spatial light modulator using ray tracing, and confirmed the validity experimentally. The transmissivity of the dispersion compensator is $\sim 30\%$. Most of the loss by the compensator is due to the gratings. Generally, a power handling capacity of a liquid crystal modulator is relatively low, so if a dispersion compensator including a liquid crystal modulator is used in a CPA system, a dispersion compensator should be used before the amplification stages. We measure the phase of the pulse, which passes through the pulse stretcher, the dispersion compensator without control, and the pulse compressor. Based on the results, we control the phase of the dispersion compensator to cancel the residual dispersion of the output pulse. Figure 7 shows the spectra of the recompressed pulse, and the phase of the recompressed pulse with (solid line) and without (dotted line) control of the dispersion compensator. This shows that the phase of the recompressed pulse is reduced to ~ 0 from ~ 700–960 nm. Figure 8 shows the measured fringe-resolved autocorrelation trace (solid line) of the recompressed pulse and the autocorrelation trace (dotted line) of the recompressed pulse calculated from the measured spectra and the measured phase. The measured pulse width is ~ 8.9 fs, and the measured and calculated autocorrelation traces agree well each other. Figure 9 shows the reconstructed pulse calculated from the measured spectra and the measured phase. The pedestal and the satellite pulses seem to be negligibly small.

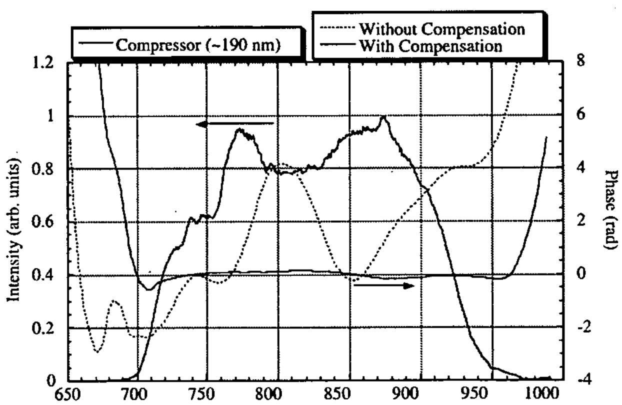

FIGURE 7 Spectra of the recompressed pulse, phase (*dotted line*) of the recompressed pulse without control of the dispersion compensator, and phase (*solid line*) of the recompressed pulse with control of the dispersion compensator

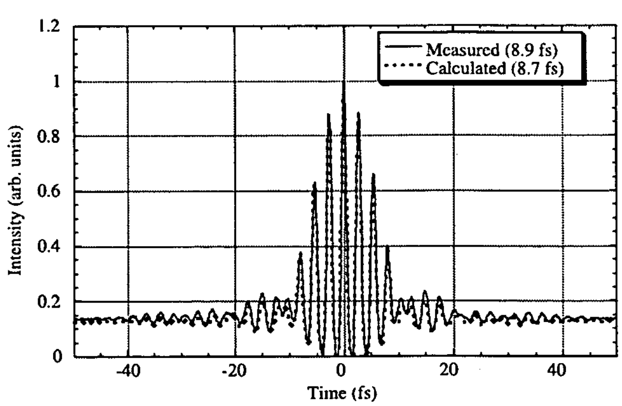

FIGURE 8 Measured fringe-resolved autocorrelation trace (*solid line*) of the recompressed pulse and autocorrelation trace (*dotted line*) of the recompressed pulse calculated from the measured spectra and the measured phase

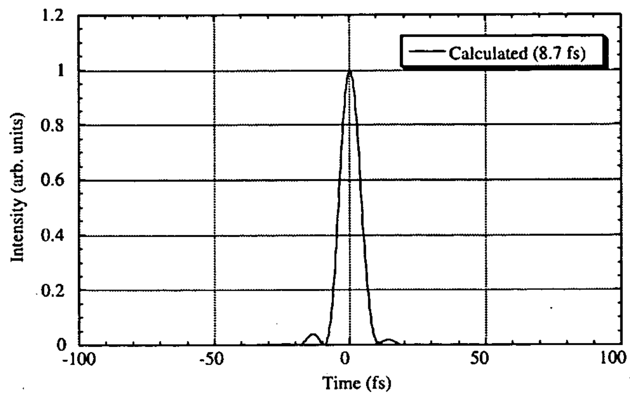

FIGURE 9 Reconstructed pulse calculated from the measured spectra and the measured phase

4 Validity of a dispersion compensator to a chirped-pulse amplification system

In our experiment, we demonstrate stretch and recompression using only a pulse stretcher, a dispersion compensator, and a pulse compressor. For the generation of $\sim$ TW, ~ 10-fs pulses, it is difficult to cancel the total dispersions of a CPA system, including a pulse stretcher, amplification stages and a pulse compressor, because generally the high order dispersions of the amplification stages are significantly different from those of a pulse stretcher or a pulse compressor. A dispersion compensator using a spatial light modulator seems to be useful for dispersion compensation of a CPA system, because a dispersion compensator generates an arbitrary dispersion. To confirm the validity of a dispersion compensator to a CPA system, we calculated the output pulse of the system including an eight-pass preamplifier and a six-pass power amplifier, considering the dispersions of materials (13-cm-long e-sapphire, 3-cm-long o-KD*P, 2.2-cm-long fused silica, 2.4-cm-long e-Calcite), a pulse stretcher, a dispersion compensator and a pulse compressor. We also consider measured residual dispersions of the pulse stretcher and the pulse compressor, and the discontinuous wavelength dependence of phases of the dispersion compensator. The output pulse is calculated from the spectra shown in Fig. 7 and the residual dispersion of the system mentioned above. Figure 10 shows the output pulse calculated from this simulation. The calculated pulse width is ~ 8.6 fs. The pedestal and the satellite pulses seem to be negligibly small. This result shows that our compensation scheme is capable for a ~ 10-fs TW CPA system.

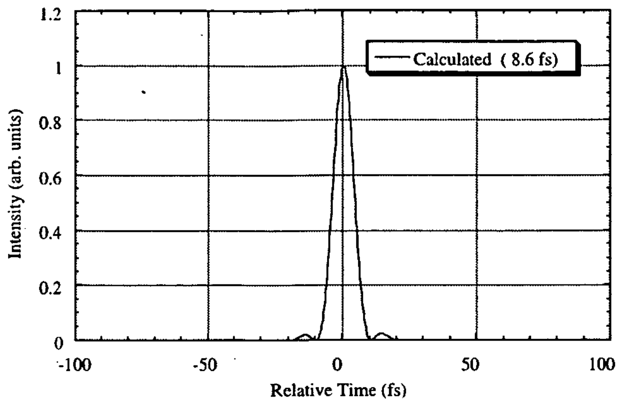

FIGURE 10 Output pulse calculated from the spectra shown in Fig. 7 and the residual dispersions of the Ti:sapphire chirped-pulse amplification system

5 Summary

We demonstrate stretch and recompression of a sub-10-fs pulse using a broadband pulse stretcher, a dispersion compensator with a spatial light modulator, and a broadband pulse compressor for a ~ 10-fs Ti:sapphire chirped-pulse amplification system. The scheme, that is a measurement of the residual dispersions of an output pulse and dispersion compensation using a spatial light modulator based on the results of measuring the residual dispersions of an output pulse, is useful for a chirped-pulse amplification system which needs large ratio stretch and recompression. We believe that the pulse stretcher, the dispersion compensator and the pulse compressor are useful for the generation of ~ 10-fs TW pulses.

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Generation of 0.1-TW optical pulses with a single-stage Ti:sapphire amplifier at a 1-kHz repetition rate

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Abstract. We present a kHz-rate all-solid-state Ti:sapphire oscillator–amplifier system producing 1.8 mJ sub-20 fs pulses using a single multipass amplifier stage pumped by ≈ 10 mJ pulses. Compensation for gain narrowing and high-order dispersion is provided by chirped dielectric multilayer optics. The focused peak intensity approaches 10^{18} W/cm^2, making this compact high-repetition-rate source attractive for a wide range of high-field applications.

PACS: 42.60.Da; 42.60.Jf; 42.60.LH

Titanium:sapphire-based oscillator–amplifier systems drawing on the concept of chirped pulse amplification have become the standard tabletop sources of high-intensity optical pulses in the last few years. At repetition rates of 10–50 Hz, the generation of pulses with multiterawatt peak power has been demonstrated [1]. More recently, amplifiers delivering pulses with peak powers beyond 0.1 TW at a 1 kHz repetition rate have also been reported [2–6]. All these systems consist of grating stretcher–compressor arrangements and several amplifier stages pumped by several Q-switched lasers, resulting in a high degree of complexity and occupying large amounts of space. In this paper we present, for what is to our knowledge the first time, a kHz laser generating 0.1 TW pulses by using a single amplifier stage and a single Q-switched pump source. Owing to a stretcher–compressor technique that obviates the need for lossy diffraction gratings [7], as much as 17% of the pump pulse energy is converted into recompressed output pulse energy. To explore the potential of this efficient and compact system for high-field applications, we have thoroughly characterized the output temporally, spectrally and spatially.

1 Modeling of the amplification process

1.1 Gain narrowing

Due to the finite fluorescence bandwith of Ti:sapphire and the huge factor of amplification, the spectral width of the input pulses is decreased by a considerable amount. To estimate the required compensation, we used a simple model for the gain-narrowing process. Making use of the atomic gain coefficient

$$\alpha(\omega) = \frac{\sigma N}{1 + [2(\omega - \omega_a)/\Delta\omega_a]^2}, \tag{1}$$

one can express the power gain as

$$G(\omega) = \exp[\alpha(\omega) L] \tag{2}$$

$$= \exp\left[\frac{\sigma N L}{1 + [2(\omega - \omega_a)/\Delta\omega_a]^2}\right], \tag{3}$$

where σ is the emission cross-section (3×10^{-19} cm^2 for Ti:sapphire [8]), N is the population inversion, ω_a is the atomic transition frequency, $\Delta\omega_a$ is the atomic linewidth and L is the total pathlength in the crystal [9]. The impact of this frequency-dependent power gain on a measured oscillator spectrum is shown in Fig. 1 for a net power gain of 10^6. The spectral width is reduced from 148 nm to 41 nm full width at half maximum (FWHM).

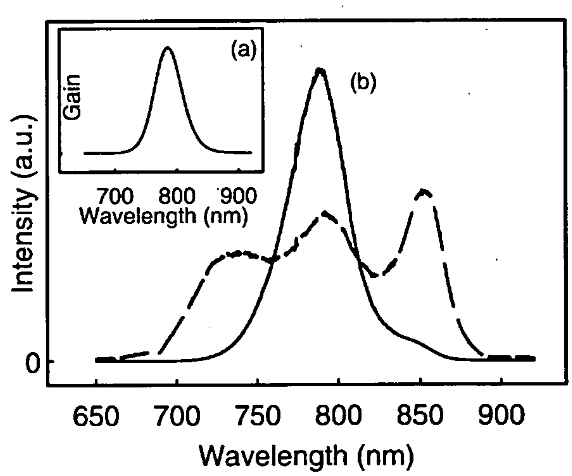

Fig. 1. **a** Power gain. **b** Measured input spectrum (*dashed*) and calculated amplified spectrum (*solid*)

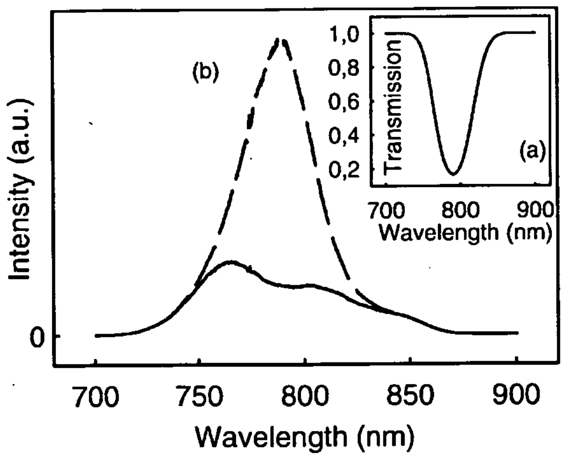

Fig. 2. **a** Filter transmission. **b** Calculated amplified spectrum with (*solid*) and without (*dashed*) filters

Using a spectral amplitude filter (Fig. 2a) one can partly compensate for gain narrowing. The spectral width is increased from 41 nm to 75 nm (Fig. 2b).

1.2 Gain saturation

As long as the population inversion is not substantially depleted, the amplification factor does not depend on the energy of the seed pulses (linear regime). In this case the so called small-signal gain is given by

$$G_{\mathrm{lin}} = \exp(\sigma N L)\,, \tag{4}$$

where σ is the emission cross-section, N is the population inversion, and L the length of the amplifier medium.

When the inversion is significantly reduced by the amplification process, the amplifier enters the saturated regime where the gain decreases with rising input-pulse energy. In this mode of operation the gain can be written as

$$G_{\mathrm{sat}} = \frac{E_{\mathrm{out}}}{E_{\mathrm{in}}} = G_{\mathrm{lin}} \exp\left(-\frac{E_{\mathrm{out}} - E_{\mathrm{in}}}{F_{\mathrm{sat}} A}\right), \tag{5}$$

with the saturation fluence $F_{\mathrm{sat}} = \hbar\omega/\sigma$ and the illuminated area A.

Operating an amplifier close to saturation allows the optimization of the energy extraction on the one hand and makes the output energy less susceptible to fluctuations of pump and seed pulses on the other hand. As the stored energy is removed by the traversing seed pulse, the leading edge will always undergo a stronger amplification than the trailing edge. This amplitude-shaping effect shifts the center of gravity of the pulse envelope forward in time, and in case of chirped pulse amplification the pulse spectrum experiences a redshift, assuming a positive chirp. Additionally, the spectral reshaping can cause a decrease of the output bandwidth, e.g. by clipping the blue end of the spectrum. A more detailed description of the amplification process is given in [10].

Furthermore, a significant limitation of the overall bandwith can be given by the mirrors, especially 45° steering mirrors in p-polarization. This restriction can be relaxed by using either s-polarization or specially designed chirped mirrors.

2 Setup

A schematic of the system is shown in Fig. 3. The mirror-dispersion-controlled Ti:sapphire oscillator (FemtoSource Pro; FemtoLasers GmbH) pumped by a diode-pumped frequency-doubled Nd:YVO$_4$ laser (Millenia; Spectra-Physics, Inc.) delivers sub-10 fs pulses of a few nJ energy at 75 MHz repetition rate. Owing to the use of broadband chirped mirrors instead of prisms for dispersion control, the bandwidth of the output extends over a range of ≈ 140 nm. Due to this broad bandwidth, the material dispersion of a 10-cm-long SF57 glass block and the Faraday isolator at the entrance of the amplifier is sufficient to stretch the pulses up to ≈ 20 ps. This grating-less streching technique provides high efficiency and no need for alignment.

After temporal shaping, the pulse train is injected into a multipass amplifier arrangement. The amplifier consists of two curved mirrors, two retroreflectors and a 3.5-mm-long Brewster-cut Ti:sapphire crystal. The highly doped Ti:sapphire crystal ($\alpha = 3.5\,\mathrm{cm}^{-1}$) is placed in a vacuum

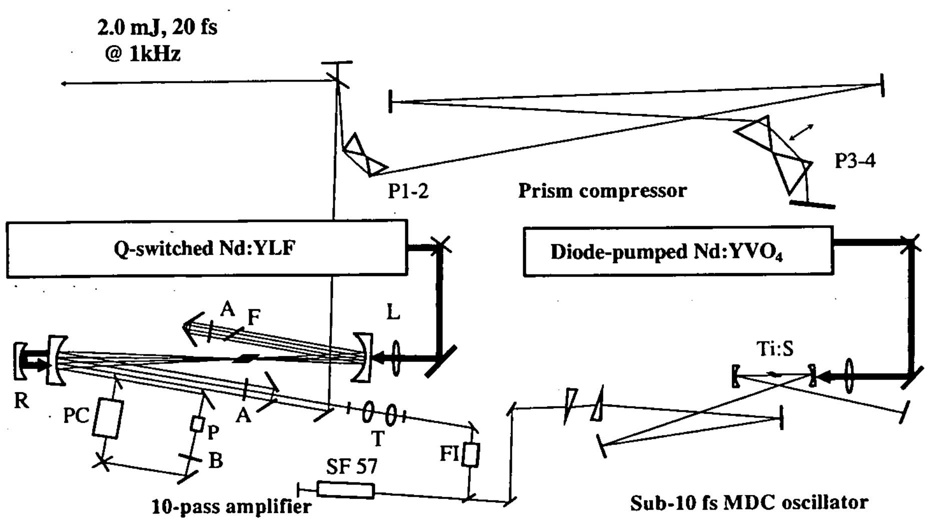

Fig. 3. Schematic of the laser system. SF57, heavy flint glass; F, shaping filter; FI, Faraday isolator; A, apertures; PC, Pockels cell; B, Berek polarization compensator; P, polarizer; T, demagnifying telescope; L, lens for pump beam; R, reflector for residual pump beam; P1-4, fused-silica prisms, numbered 1–4

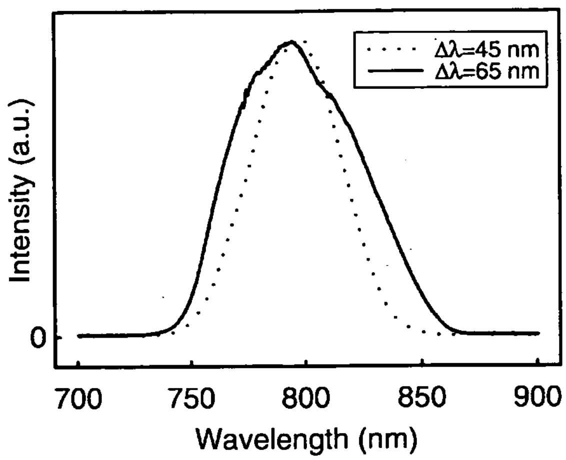

Fig. 4. Effect of the specially designed spectral shaping filter. Measured amplified spectrum without (*dotted*) and with (*solid*) filter

chamber and is thermo-electrically cooled down to −15 °C to reduce the effect of thermal lensing. One of the retroreflectors is made up of two chirped mirrors specially designed for providing third- and fourth-order dispersion control to compensate for the higher-order-dispersion of the prism compressor and all the material in the amplifier.

During the first four passes, the pulses go through a dielectric multilayer filter providing the total transmission curve shown in Fig. 2a. Thus gain narrowing is partially compensated for, increasing the amplified bandwidth by ≈ 50% (Fig. 4). This spectral reshaping is at nearly no cost to overall power gain because of the strong saturation of the amplifier. In contrast with etalons or birefringent plates previously used for amplitude shaping, dielectric filters allow almost arbitrary transmission characteristics.

After four passes through the crystal, a single pulse is selected out of the pulse train with a Pockels cell. In this way both the ASE background and the susceptibility to lasing are suppressed. The measured ASE energy contained in the 10 ns Pockels cell time window is 2.7 μJ, yielding a pulse-to-pedestal intensity contrast of $\approx 10^9$.

The selected single pulse is reinjected and amplified in another six passes, where it picks up an additional 1-μs-long ASE background of 210 nJ energy. Before the last two passes, the pulse is coupled-out once again and reinjected after a reduction of the beam diameter by a factor of two. This allows optimization of the mode overlap of pump and seed beam, thus maximizing the energy extraction in the last two passes. In addition, nonlinear effects in the gain medium are reduced, keeping the B-integral low (of the order of unity). Pumping this optimized amplifier with 10.5 mJ from a lamp-pumped Q-switched frequency-doubled Nd:YLF laser results in a pulse energy of 2 mJ.

The amplified pulses are compressed with a prism compressor consisting of two pairs of Brewster-angled fused-silica prisms separated by 6 m. After passage through the prism compressor, the pulse duration is less than 20 fs and the beam diameter is 25 mm. The good energy extraction efficiency in the amplifier and the high throughput of the prism compressor (≈ 90%) results in an overall efficiency (from nanosecond pump pulses into femtosecond amplified pulses) of 17%.

3 Characterization

Using these pulses for experiments, such as studying the interaction of intense laser fields with matter, calls for a precise knowledge of the pulse characteristics. To this end, we have characterized the temporal evolution with a SHG-FROG [11, 12] apparatus and, over an enhanced dynamic range, with a third-order autocorrelator, the beam quality and focusability with a CCD camera, and the spectrum with a grating spectrograph.

A typical SHG-FROG trace is shown in Fig. 5. The retrieved pulses have a duration of 17.5 fs and a bandwidth of 65 nm. The retrieved amplitude spectrum fits well to the one measured; and the spectral phase is reasonably flat over the whole spectral range, indicating a proper compensation of phase errors.

Figure 6 shows a high-dynamic-range autocorrelation based on third-harmonic generation directly on a glass surface [13]. It indicates a drop of the intensity of nearly three orders of magnitude within 100 fs at the leading edge and four orders of magnitude within less than 350 fs. Previous experiments have shown that, if required for certain experimental applications, the leading pulse edge can be steepened up by application of positive TOD [13].

We have also performed an M^2 measurement, yielding a value of approximately 1.5 in both planes. For this purpose we focused the beam with f/100 optics and recorded the beam diameters (x- and y-plane) at several positions in front and be-

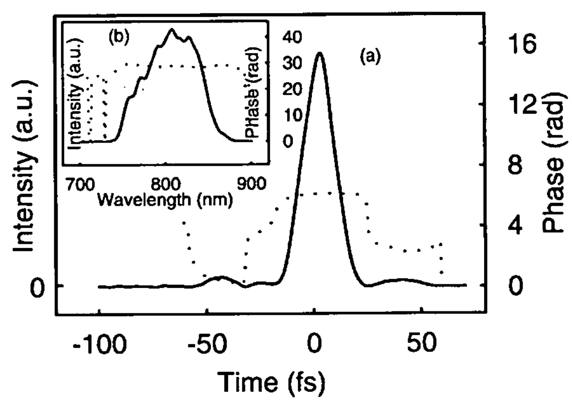

Fig. 5a,b. Measured SHG-FROG. a Temporal intensity (*solid*) and phase (*dotted*). b Spectral intensity and phase

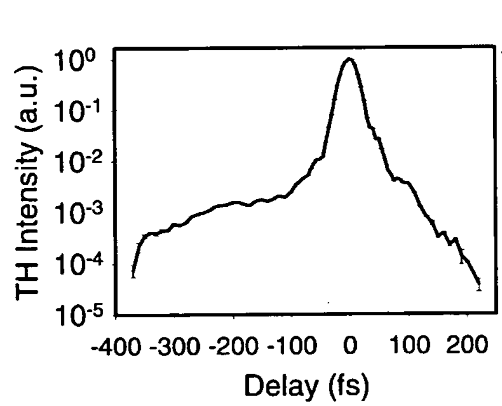

Fig. 6. Measured THG-autocorrelation

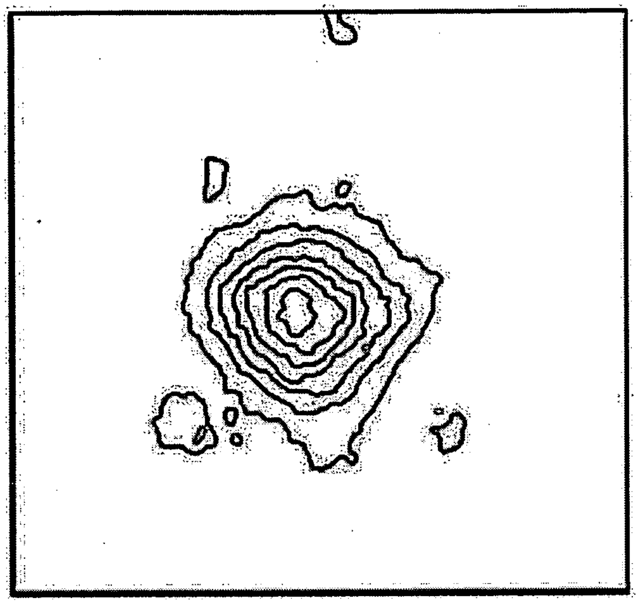

Fig. 7. Focal spot of 3.5 μm diameter

hind a beam waist with a CCD camera. For evaluation of M^2, its defining equation [9]

$$w(z) = w_0\sqrt{1+\left[M^2\left(\frac{z}{z_R}\right)\right]^2} \qquad (6)$$

has been fitted to the measured data. Here w is the measured beam radius, w_0 the radius at the beam waist, z the longitudinal coordinate and z_R the rayleigh range given by $w_0^2\pi/\lambda$.

By utilizing a diamond-turned off-axis parabolic mirror of 33 mm focal length (f/1.3 optics), some 70% of the pulse energy can be concentrated within a spot of a $1/e^2$ diameter of 3.5 μm, which was imaged with a 100× microscope objective onto a CCD camera. This results in a peak intensity of approximately 6×10^{17} W/cm^2. The contour plot in Fig. 7 depicts isointensity lines at the levels of $I_p/8$, where I_p is the peak intensity in the focal plane. The distortions surrounding the central spot originate from the mirror itself, since the surface of a diamond-turned mirror exhibits grooves acting as a grating. In this manner some 10% of the energy is defracted into higher-order modes.

4 Conclusions

We have demonstrated the kHz-rate generation of femtosecond pulses at the 0.1 TW level from a single-stage amplifier for the first time. A detailed characterization yields sub-20 fs pulse duration, a drop in the intensity by more than four orders of magnitude at 350 fs prior to the peak of the pulse, and a focused peak intensity close to 10^{18} W/cm^2. These characteristics open the way to performing high-field experiments at a high repetition rate with a compact (occupied table space: ≈ 2.5 m^2) user-friendly system. Furthermore, this source has the potential to be scaled up to output energies of ≈ 10 mJ, implementing a second amplifier stage.

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